

## NONTHERMAL Mg I EMISSION AT 12 MICRON FROM PROCYON

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### ABSTRACT

We report on stellar Mg I emission at 12  $\mu\text{m}$  from  $\alpha$  CMi (Procyon), a star slightly hotter than the Sun. Solar Mg I emission is well known, and its formation was successfully explained in detail by Carlsson et al. Here, for the first time, we successfully model and compare synthetic spectra of the emission lines at 12  $\mu\text{m}$  with observations of a star other than the Sun. The use of these lines as stellar diagnostics has been anticipated for 10 years or more (see, e.g., Carlsson et al.). We find that the model reproduces the observed emission in Procyon quite well. We expect that high-resolution spectrographs on 8–10 m telescopes will finally be able to exploit these new diagnostics.

*Subject headings:* infrared: stars — stars: atmospheres — stars: individual ( $\alpha$  Canis Minoris)

### 1. INTRODUCTION

The origin and formation process of the once enigmatic *solar* Mg I emission at 811.578  $\text{cm}^{-1}$  (12.3217  $\mu\text{m}$ ) and 818.058  $\text{cm}^{-1}$  (12.2241  $\mu\text{m}$ ) were first explained successfully and in detail by Carlsson et al. (1992, hereafter C92). By employing an extensive model atom of Mg I in a full non-LTE (NLTE) calculation, they concluded that the emission lines were photospheric in origin. C92 accounted excellently for the emission strengths of the Mg I lines, their complicated intensity profiles as a function of viewing angle on the solar disk, and the relative strengths of several Mg I lines, both in emission and in absorption. Furthermore, C92 could explain the similar but weaker Si I and Al I emission features observed in the solar spectrum. Baumüller & Gehren (1996) successfully modeled these Al I emission features in the Sun, showing that a similar NLTE effect as for Mg I is responsible. Zhao et al. (1998) were also able to reproduce the solar emission lines with a similar NLTE analysis of magnesium in the solar photosphere. Moreover, by including artificially reduced, inelastic neutral-hydrogen collisions, they were also able to simultaneously model line cores of visual and near-infrared (NIR) Mg I absorption lines in the range of 4500–12,000 Å.

The Mg I emission lines at 12  $\mu\text{m}$  in the Sun clearly show Zeeman splitting and so trace the local magnetic field (Brault & Noyes 1983; Bruls et al. 1995). Because Zeeman splitting depends on the square of the wavelength while Doppler broadening goes as the first power, mid-infrared lines better reveal Zeeman splitting than optical or NIR lines with the same Landé  $g$ -factor. Thus, these lines potentially offer an excellent method for measuring stellar disk-averaged magnetic fields and will be complementary to studies using NIR lines in that they will probe other atmospheric layers and are more Zeeman sensitive.

In this Letter we report on our detection and modeling of the mid-infrared Mg I emission features in Procyon, an F5 IV–V star. In the Sun, the observed emission lines are formed as a result of an NLTE flow cycle. As lines originating from high-

excitation levels become optically thin in the photosphere, lower lying levels are overpopulated and subsequently photoionized. The Mg II reservoir refills the high-excitation levels via Rydberg states of Mg I, leading to the emission.

From NLTE calculations, the relevant departures from Boltzmann level populations for the levels involved— $3s7i\ ^{1,3}I^e$  and  $3s6h\ ^{1,3}H^o$  for the 811.6  $\text{cm}^{-1}$  line and  $3s7h\ ^{1,3}H^o$  and  $3s6g\ ^{1,3}G^e$  for the 818.1  $\text{cm}^{-1}$  line—are quite similar for both the upper and lower states. The departure coefficients of the upper levels are of the order of 10% larger than those of the lower states. However, this small difference between the level departures is the direct cause of the observed emission.

### 2. OBSERVATIONS

We observed Procyon with the Texas Echelon Cross Echelle Spectrograph (TEXES; Lacy et al. 2002), a visitor instrument at the 3 m NASA Infrared Telescope Facility (IRTF). The raw data were collected during 2000 November, 2001 November, 2002 December, 2003 December, and 2004 January. Separate grating settings were required for each Mg I line.

We used the cross-dispersed high spectral resolution mode for all observations. Observations of unresolved line sources indicate that the core of the line profile at this wavelength is reasonably reproduced with a Gaussian with FWHM = 3.5  $\text{km s}^{-1}$  ( $R \sim 86,000$ ) and wings that are slightly broader than Gaussian.

Data acquisition and reduction followed the standard procedure described in Lacy et al. (2002). To remove sky and telescope background, Procyon was nodded along the slit. Wavelength calibration was done using telluric atmospheric lines; previous experience shows that this procedure typically gives accuracy better than 1  $\text{km s}^{-1}$ . After reducing a given data set, we normalized the continuum using a sixth-order Legendre polynomial and then combined appropriate data files. Procyon has almost no photospheric features at this wavelength, so determining the continuum is easy and reliable. Furthermore, the telluric atmosphere at the Mg I wavelengths is very clean. Slight variations in wavelength setting from night to night result in increased noise where less data could be co-added.

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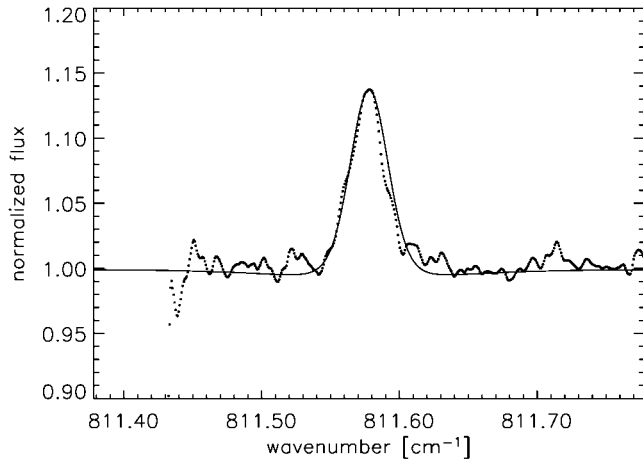


FIG. 1.—Dotted line shows the Mg I emission line at  $811.578 \text{ cm}^{-1}$  ( $12.3217 \text{ }\mu\text{m}$ ) observed from Procyon, and the solid line shows the model.

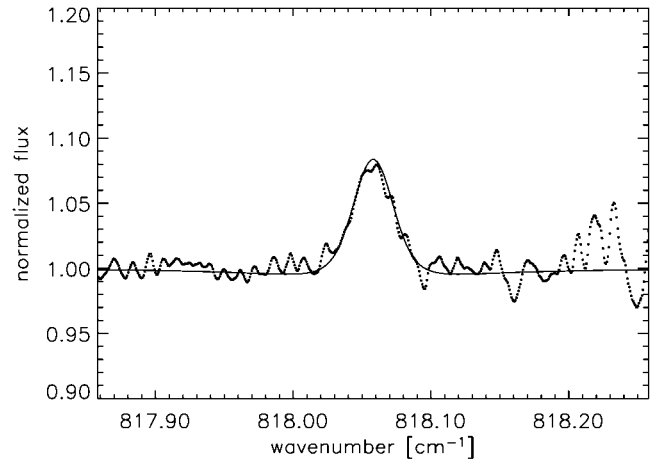


FIG. 2.—Dotted line depicts the  $818.058 \text{ cm}^{-1}$  ( $12.2241 \text{ }\mu\text{m}$ ) Mg I line observed from Procyon. As in Fig. 1, the model prediction is shown by a solid line.

### 3. MODELING

We have analyzed the Procyon Mg I lines as C92 successfully did for the Mg I lines in the Sun. We use a one-dimensional, hydrostatic, flux-conserved, nonmagnetic LTE model for the physical structure of the atmosphere. The model atmosphere, including the specific mean-intensity field at all depths, is calculated with the MARCS code, which was first developed by Gustafsson et al. (1975) and has been successively updated ever since (B. Gustafsson et al. 2004, in preparation).

For the line formation of Mg I and the spectral synthesis, a full NLTE calculation is performed using the program MULTI (Carlsson 1986). Our Mg I model atom was kindly provided by M. Carlsson. We require our model to reproduce the excellent fits of the intensity profiles measured at different locations on the solar disk as presented in C92.

We solve the equations of statistical equilibrium for the magnesium atom level populations at each of 66 levels, including 315 line transitions and 65 bound-free transitions (ionization and recombination). One Mg II level is included. We calculate photoionization rates by incorporating the calculated specific mean-intensity field for all depths from the model atmosphere. This treatment allows the full line-blanketing to be considered through ultraviolet wavelengths, which mainly affect the photoionization from the lowest states. For a further discussion, references for the atomic data, and the uncertainties in the modeled emission, see C92.

The fundamental stellar parameters of Procyon, needed in the calculation of the model atmosphere, are relatively well known. All parameters, except the metallicity, can be derived from direct measurements. Recent works determining Procyon's parameters include Fuhrmann (1998), Allende Prieto et al. (2002), and Korn et al. (2003). The parameters that we have used are an effective temperature of  $T_{\text{eff}} = 6512 \pm 50 \text{ K}$ , a surface gravity of  $\log g = 3.96 \pm 0.02$  (in units of cgs), a mass of  $M = 1.42 \pm 0.06 M_{\odot}$ , and a radius of  $R = 2.07 \pm 0.02 R_{\odot}$  (Allende Prieto et al. 2002). The metallicity (iron abundance) of the star is slightly lower than solar. Fuhrmann (1998) measures a slightly supersolar  $\alpha$ -element abundance. Nevertheless, we assume a solar abundance mixture as given by Grevesse & Sauval (1998). We model the atmosphere with a depth-independent microturbulence parameter of  $\xi_{\text{micro}} = 2.0 \text{ km s}^{-1}$ , in agreement with current literature.

### 4. RESULTS AND DISCUSSION

Our model and observations are shown in Figures 1 and 2. In order to match the line widths, we introduce the customary artifact of macroturbulent broadening, including the instrumental profile. We assume that the broadening velocities have a Gaussian distribution with a FWHM of  $9.5 \text{ km s}^{-1}$ , which is slightly larger than that given in Allende Prieto et al. (2002). We find that the model reproduces the disk-averaged observations within the modeling uncertainties. In a forthcoming paper we will investigate our calculation by discussing the atomic model of Mg I and the assumptions made in our NLTE calculation, such as the collisional rates, atmospheric radiation field used, and the validity of the assumption of atmospheric homogeneity.

In Figure 3, the departure coefficients (defined as in C92) of the relevant levels are plotted as a function of depth in the atmosphere, shown as the optical depth calculated in the continuum at 500 nm. The departure coefficients are very similar to the solar case, indicating that the same formation process of the Mg I emission lines is at play for Procyon. Following

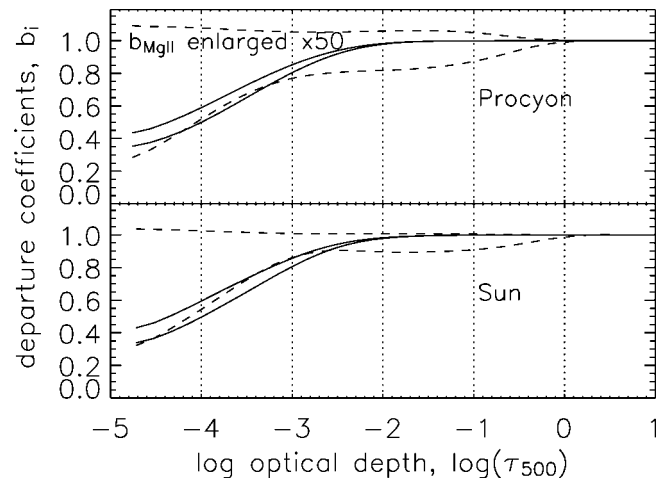


FIG. 3.—Departure coefficients for the levels involved in the two emission lines are shown with solid lines. The top dashed line shows the departure coefficient of Mg II, and the bottom dashed line shows the ground level of Mg I.

C92, we have included “quasi-elastic  $l$ -changing”<sup>3</sup> collisions with neutral particles, which keep all close-lying Rydberg states with common principal quantum numbers  $n$  in relative thermalization. This means that the departure coefficients of the upper and lower states, respectively, of the two Mg I emission lines will follow each other exactly since they have the same  $n$  quantum numbers. Thus, in Figure 3 the upper and lower levels of the two Mg I emission lines fall on top of each other. The lower levels depart more from LTE. Whereas for the Sun the population of Mg II is slightly larger than that of LTE, for Procyon the Mg II population is very close to LTE.

The Mg I emission in Procyon is only marginally larger than that of the Sun. This fact can be qualitatively understood as follows. The higher temperatures in Procyon compared to the Sun will lead to a larger ionization of magnesium, with a factor of 10 less Mg I expected all through the line-forming regions. However, in the line-forming regions of Procyon, the 500 K warmer temperatures compared to the Sun also lead to roughly a factor of 10 more atoms excited to the levels involved in the formation of the emission line. Since the departure coefficients for both Procyon and the Sun are quite similar, the resulting emission will be of the same order of magnitude for both stars, as observed.

<sup>3</sup> With  $l$  being the azimuthal quantum number.

To conclude, we have shown that with an NLTE calculation using the C92 model atom of magnesium, it is possible to reproduce Mg I emission lines at 12  $\mu\text{m}$  successfully, not only for the Sun but also for Procyon. This is the first star other than the Sun that this has been done for. Future investigations of different types of stars, showing Mg I emission lines, will also be important. The Mg I emission lines should be useful tools for measuring stellar magnetic fields through their Zeeman splitting. After a decade of anticipation, high-resolution mid-IR spectrographs, such as TEXES, at 8–10 m telescopes will now allow the use of the Mg I 12  $\mu\text{m}$  lines for stellar magnetic field diagnostics.

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